

# Search for heavy bottom-like quarks decaying to an electron or muon and jets in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

T. Aaltonen,<sup>22</sup> B. Álvarez González<sup>v</sup>,<sup>10</sup> S. Amerio,<sup>42</sup> D. Amidei,<sup>33</sup> A. Anastassov,<sup>37</sup> A. Annovi,<sup>18</sup> J. Antos,<sup>13</sup> G. Apollinari,<sup>16</sup> J.A. Appel,<sup>16</sup> A. Apresyan,<sup>47</sup> T. Arisawa,<sup>57</sup> A. Artikov,<sup>14</sup> J. Asaadi,<sup>52</sup> W. Ashmanskas,<sup>16</sup> B. Auerbach,<sup>60</sup> A. Aurisano,<sup>52</sup> F. Azfar,<sup>41</sup> W. Badgett,<sup>16</sup> A. Barbaro-Galtieri,<sup>27</sup> V.E. Barnes,<sup>47</sup> B.A. Barnett,<sup>24</sup> P. Barria<sup>cc</sup>,<sup>45</sup> P. Bartos,<sup>13</sup> M. Bauce<sup>aa</sup>,<sup>42</sup> G. Bauer,<sup>31</sup> F. Bedeschi,<sup>45</sup> D. Beecher,<sup>29</sup> S. Behari,<sup>24</sup> G. Bellettini<sup>bb</sup>,<sup>45</sup> J. Bellinger,<sup>59</sup> D. Benjamin,<sup>15</sup> A. Beretvas,<sup>16</sup> A. Bhatti,<sup>49</sup> M. Binkley<sup>\*</sup>,<sup>16</sup> D. Bisello<sup>aa</sup>,<sup>42</sup> I. Bizjak<sup>gg</sup>,<sup>29</sup> K.R. Bland,<sup>5</sup> B. Blumenfeld,<sup>24</sup> A. Bocci,<sup>15</sup> A. Bodek,<sup>48</sup> D. Bortoletto,<sup>47</sup> J. Boudreau,<sup>46</sup> A. Boveia,<sup>12</sup> B. Brau<sup>a</sup>,<sup>16</sup> L. Brigliadori<sup>z</sup>,<sup>6</sup> A. Brisuda,<sup>13</sup> C. Bromberg,<sup>34</sup> E. Brucken,<sup>22</sup> M. Bucciantonio<sup>bb</sup>,<sup>45</sup> J. Budagov,<sup>14</sup> H.S. Budd,<sup>48</sup> S. Budd,<sup>23</sup> K. Burkett,<sup>16</sup> G. Busetto<sup>aa</sup>,<sup>42</sup> P. Bussey,<sup>20</sup> A. Buzatu,<sup>32</sup> C. Calancha,<sup>30</sup> S. Camarda,<sup>4</sup> M. Campanelli,<sup>34</sup> M. Campbell,<sup>33</sup> F. Canelli<sup>12</sup>,<sup>16</sup> A. Canepa,<sup>44</sup> B. Carls,<sup>23</sup> D. Carlsmith,<sup>59</sup> R. Carosi,<sup>45</sup> S. Carrillo<sup>k</sup>,<sup>17</sup> S. Carron,<sup>16</sup> B. Casal,<sup>10</sup> M. Casarsa,<sup>16</sup> A. Castro<sup>z</sup>,<sup>6</sup> P. Catastini,<sup>16</sup> D. Cauz,<sup>53</sup> V. Cavaliere<sup>cc</sup>,<sup>45</sup> M. Cavalli-Sforza,<sup>4</sup> A. Cerri<sup>f</sup>,<sup>27</sup> L. Cerrito<sup>q</sup>,<sup>29</sup> Y.C. Chen,<sup>1</sup> M. Chertok,<sup>7</sup> G. Chiarelli,<sup>45</sup> G. Chlachidze,<sup>16</sup> F. Chlebana,<sup>16</sup> K. Cho,<sup>26</sup> D. Chokheli,<sup>14</sup> J.P. Chou,<sup>21</sup> W.H. Chung,<sup>59</sup> Y.S. Chung,<sup>48</sup> C.I. Ciobanu,<sup>43</sup> M.A. Ciocci<sup>cc</sup>,<sup>45</sup> A. Clark,<sup>19</sup> G. Compostella<sup>aa</sup>,<sup>42</sup> M.E. Convery,<sup>16</sup> J. Conway,<sup>7</sup> M. Corbo,<sup>43</sup> M. Cordelli,<sup>18</sup> C.A. Cox,<sup>7</sup> D.J. Cox,<sup>7</sup> F. Crescioli<sup>bb</sup>,<sup>45</sup> C. Cuenca Almenar,<sup>60</sup> J. Cuevas<sup>v</sup>,<sup>10</sup> R. Culbertson,<sup>16</sup> D. Dagenhart,<sup>16</sup> N. d'Ascenzo<sup>t</sup>,<sup>43</sup> M. Datta,<sup>16</sup> P. de Barbaro,<sup>48</sup> S. De Cecco,<sup>50</sup> G. De Lorenzo,<sup>4</sup> M. Dell'Orso<sup>bb</sup>,<sup>45</sup> C. Deluca,<sup>4</sup> L. Demortier,<sup>49</sup> J. Deng<sup>c</sup>,<sup>15</sup> M. Deninno,<sup>6</sup> F. Devoto,<sup>22</sup> M. d'Errico<sup>aa</sup>,<sup>42</sup> A. Di Canto<sup>bb</sup>,<sup>45</sup> B. Di Ruzza,<sup>45</sup> J.R. Dittmann,<sup>5</sup> M. D'Onofrio,<sup>28</sup> S. Donati<sup>bb</sup>,<sup>45</sup> P. Dong,<sup>16</sup> M. Dorigo,<sup>53</sup> T. Dorigo,<sup>42</sup> K. Ebina,<sup>57</sup> A. Elagin,<sup>52</sup> A. Eppig,<sup>33</sup> R. Erbacher,<sup>7</sup> D. Errede,<sup>23</sup> S. Errede,<sup>23</sup> N. Ershaidat<sup>y</sup>,<sup>43</sup> R. Eusebi,<sup>52</sup> H.C. Fang,<sup>27</sup> S. Farrington,<sup>41</sup> M. Feindt,<sup>25</sup> J.P. Fernandez,<sup>30</sup> C. Ferrazza<sup>dd</sup>,<sup>45</sup> R. Field,<sup>17</sup> G. Flanagan<sup>r</sup>,<sup>47</sup> R. Forrest,<sup>7</sup> M.J. Frank,<sup>5</sup> M. Franklin,<sup>21</sup> J.C. Freeman,<sup>16</sup> Y. Funakoshi,<sup>57</sup> I. Furic,<sup>17</sup> M. Gallinaro,<sup>49</sup> J. Galyardt,<sup>11</sup> J.E. Garcia,<sup>19</sup> A.F. Garfinkel,<sup>47</sup> P. Garosi<sup>cc</sup>,<sup>45</sup> H. Gerberich,<sup>23</sup> E. Gerchtein,<sup>16</sup> S. Giagu<sup>ee</sup>,<sup>50</sup> V. Giakoumopoulou,<sup>3</sup> P. Giannetti,<sup>45</sup> K. Gibson,<sup>46</sup> C.M. Ginsburg,<sup>16</sup> N. Giokaris,<sup>3</sup> P. Giromini,<sup>18</sup> M. Giunta,<sup>45</sup> G. Giurciu,<sup>24</sup> V. Glagolev,<sup>14</sup> D. Glenzinski,<sup>16</sup> M. Gold,<sup>36</sup> D. Goldin,<sup>52</sup> N. Goldschmidt,<sup>17</sup> A. Golossanov,<sup>16</sup> G. Gomez,<sup>10</sup> G. Gomez-Ceballos,<sup>31</sup> M. Goncharov,<sup>31</sup> O. González,<sup>30</sup> I. Gorelov,<sup>36</sup> A.T. Goshaw,<sup>15</sup> K. Goulianos,<sup>49</sup> A. Gresele,<sup>42</sup> S. Grinstein,<sup>4</sup> C. Grosso-Pilcher,<sup>12</sup> R.C. Group,<sup>56</sup> J. Guimaraes da Costa,<sup>21</sup> Z. Gunay-Unalan,<sup>34</sup> C. Haber,<sup>27</sup> S.R. Hahn,<sup>16</sup> E. Halkiadakis,<sup>51</sup> A. Hamaguchi,<sup>40</sup> J.Y. Han,<sup>48</sup> F. Happacher,<sup>18</sup> K. Hara,<sup>54</sup> D. Hare,<sup>51</sup> M. Hare,<sup>55</sup> R.F. Harr,<sup>58</sup> K. Hatakeyama,<sup>5</sup> C. Hays,<sup>41</sup> M. Heck,<sup>25</sup> J. Heinrich,<sup>44</sup> M. Herndon,<sup>59</sup> S. Hewamanage,<sup>5</sup> D. Hidas,<sup>51</sup> A. Hocker,<sup>16</sup> W. Hopkins<sup>g</sup>,<sup>16</sup> D. Horn,<sup>25</sup> S. Hou,<sup>1</sup> R.E. Hughes,<sup>38</sup> M. Hurwitz,<sup>12</sup> U. Husemann,<sup>60</sup> N. Hussain,<sup>32</sup> M. Hussein,<sup>34</sup> J. Huston,<sup>34</sup> G. Introzzi,<sup>45</sup> M. Iori<sup>ee</sup>,<sup>50</sup> A. Ivanov<sup>o</sup>,<sup>7</sup> E. James,<sup>16</sup> D. Jang,<sup>11</sup> B. Jayatilaka,<sup>15</sup> E.J. Jeon,<sup>26</sup> M.K. Jha,<sup>6</sup> S. Jindariani,<sup>16</sup> W. Johnson,<sup>7</sup> M. Jones,<sup>47</sup> K.K. Joo,<sup>26</sup> S.Y. Jun,<sup>11</sup> T.R. Junk,<sup>16</sup> T. Kamon,<sup>52</sup> P.E. Karchin,<sup>58</sup> Y. Kato<sup>n</sup>,<sup>40</sup> W. Ketchum,<sup>12</sup> J. Keung,<sup>44</sup> V. Khotilovich,<sup>52</sup> B. Kilminster,<sup>16</sup> D.H. Kim,<sup>26</sup> H.S. Kim,<sup>26</sup> H.W. Kim,<sup>26</sup> J.E. Kim,<sup>26</sup> M.J. Kim,<sup>18</sup> S.B. Kim,<sup>26</sup> S.H. Kim,<sup>54</sup> Y.K. Kim,<sup>12</sup> N. Kimura,<sup>57</sup> M. Kirby,<sup>16</sup> S. Klimenko,<sup>17</sup> K. Kondo,<sup>57</sup> D.J. Kong,<sup>26</sup> J. Konigsberg,<sup>17</sup> A.V. Kotwal,<sup>15</sup> M. Kreps,<sup>25</sup> J. Kroll,<sup>44</sup> D. Krop,<sup>12</sup> N. Krumnack<sup>l</sup>,<sup>5</sup> M. Kruse,<sup>15</sup> V. Krutelyov<sup>d</sup>,<sup>52</sup> T. Kuhr,<sup>25</sup> M. Kurata,<sup>54</sup> S. Kwang,<sup>12</sup> A.T. Laasanen,<sup>47</sup> S. Lami,<sup>45</sup> S. Lammel,<sup>16</sup> M. Lancaster,<sup>29</sup> R.L. Lander,<sup>7</sup> K. Lannon<sup>u</sup>,<sup>38</sup> A. Lath,<sup>51</sup> G. Latino<sup>cc</sup>,<sup>45</sup> I. Lazzizzera,<sup>42</sup> T. LeCompte,<sup>2</sup> E. Lee,<sup>52</sup> H.S. Lee,<sup>12</sup> J.S. Lee,<sup>26</sup> S.W. Lee<sup>w</sup>,<sup>52</sup> S. Leo<sup>bb</sup>,<sup>45</sup> S. Leone,<sup>45</sup> J.D. Lewis,<sup>16</sup> C.-J. Lin,<sup>27</sup> J. Linacre,<sup>41</sup> M. Lindgren,<sup>16</sup> E. Lipeles,<sup>44</sup> A. Lister,<sup>19</sup> D.O. Litvintsev,<sup>16</sup> C. Liu,<sup>46</sup> Q. Liu,<sup>47</sup> T. Liu,<sup>16</sup> S. Lockwitz,<sup>60</sup> N.S. Lockyer,<sup>44</sup> A. Loginov,<sup>60</sup> D. Lucchesi<sup>aa</sup>,<sup>42</sup> J. Lueck,<sup>25</sup> P. Lujan,<sup>27</sup> P. Lukens,<sup>16</sup> G. Lungu,<sup>49</sup> J. Lys,<sup>27</sup> R. Lysak,<sup>13</sup> R. Madrak,<sup>16</sup> K. Maeshima,<sup>16</sup> K. Makhoul,<sup>31</sup> P. Maksimovic,<sup>24</sup> S. Malik,<sup>49</sup> G. Manca<sup>b</sup>,<sup>28</sup> A. Manousakis-Katsikakis,<sup>3</sup> F. Margaroli,<sup>47</sup> C. Marino,<sup>25</sup> M. Martínez,<sup>4</sup> R. Martínez-Ballarín,<sup>30</sup> P. Mastrandrea,<sup>50</sup> M. Mathis,<sup>24</sup> M.E. Mattson,<sup>58</sup> P. Mazzanti,<sup>6</sup> K.S. McFarland,<sup>48</sup> P. McIntyre,<sup>52</sup> R. McNulty<sup>i</sup>,<sup>28</sup> A. Mehta,<sup>28</sup> P. Mehtala,<sup>22</sup> A. Menzione,<sup>45</sup> C. Mesropian,<sup>49</sup> T. Miao,<sup>16</sup> D. Mietlicki,<sup>33</sup> A. Mitra,<sup>1</sup> H. Miyake,<sup>54</sup> S. Moed,<sup>21</sup> N. Moggi,<sup>6</sup> M.N. Mondragon<sup>k</sup>,<sup>16</sup> C.S. Moon,<sup>26</sup> R. Moore,<sup>16</sup> M.J. Morello,<sup>16</sup> J. Morlock,<sup>25</sup> P. Movilla Fernandez,<sup>16</sup> A. Mukherjee,<sup>16</sup> Th. Muller,<sup>25</sup> P. Murat,<sup>16</sup> M. Mussini<sup>z</sup>,<sup>6</sup> J. Nachtman<sup>m</sup>,<sup>16</sup> Y. Nagai,<sup>54</sup> J. Naganoma,<sup>57</sup> I. Nakano,<sup>39</sup> A. Napier,<sup>55</sup> J. Nett,<sup>52</sup> C. Neu,<sup>56</sup> M.S. Neubauer,<sup>23</sup> J. Nielsen<sup>e</sup>,<sup>27</sup> L. Nodulman,<sup>2</sup> O. Norniella,<sup>23</sup> E. Nurse,<sup>29</sup> L. Oakes,<sup>41</sup> S.H. Oh,<sup>15</sup> Y.D. Oh,<sup>26</sup> I. Oksuzian,<sup>56</sup> T. Okusawa,<sup>40</sup> R. Orava,<sup>22</sup> L. Ortolan,<sup>4</sup> S. Pagan Griso<sup>aa</sup>,<sup>42</sup> C. Pagliarone,<sup>53</sup> E. Palencia<sup>f</sup>,<sup>10</sup> V. Papadimitriou,<sup>16</sup> A.A. Paramonov,<sup>2</sup> J. Patrick,<sup>16</sup> G. Pauletta<sup>ff</sup>,<sup>53</sup> M. Paulini,<sup>11</sup> C. Paus,<sup>31</sup> D.E. Pellett,<sup>7</sup> A. Penzo,<sup>53</sup> T.J. Phillips,<sup>15</sup> G. Piacentino,<sup>45</sup> E. Pianori,<sup>44</sup> J. Pilot,<sup>38</sup> K. Pitts,<sup>23</sup> C. Plager,<sup>9</sup> L. Pondrom,<sup>59</sup>

K. Potamianos,<sup>47</sup> O. Poukhov\*,<sup>14</sup> F. Prokoshin<sup>x</sup>,<sup>14</sup> A. Pronko,<sup>16</sup> F. Ptohos<sup>h</sup>,<sup>18</sup> E. Pueschel,<sup>11</sup> G. Punzi<sup>bb</sup>,<sup>45</sup> J. Pursley,<sup>59</sup> A. Rahaman,<sup>46</sup> V. Ramakrishnan,<sup>59</sup> N. Ranjan,<sup>47</sup> I. Redondo,<sup>30</sup> P. Renton,<sup>41</sup> M. Rescigno,<sup>50</sup> F. Rimondi<sup>z</sup>,<sup>6</sup> L. Ristori<sup>45</sup>,<sup>16</sup> A. Robson,<sup>20</sup> T. Rodrigo,<sup>10</sup> T. Rodriguez,<sup>44</sup> E. Rogers,<sup>23</sup> S. Rolli,<sup>55</sup> R. Roser,<sup>16</sup> M. Rossi,<sup>53</sup> F. Rubbo,<sup>16</sup> F. Ruffini<sup>cc</sup>,<sup>45</sup> A. Ruiz,<sup>10</sup> J. Russ,<sup>11</sup> V. Rusu,<sup>16</sup> A. Safonov,<sup>52</sup> W.K. Sakumoto,<sup>48</sup> Y. Sakurai,<sup>57</sup> L. Santi<sup>ff</sup>,<sup>53</sup> L. Sartori,<sup>45</sup> K. Sato,<sup>54</sup> V. Saveliev<sup>t</sup>,<sup>43</sup> A. Savoy-Navarro,<sup>43</sup> P. Schlabach,<sup>16</sup> A. Schmidt,<sup>25</sup> E.E. Schmidt,<sup>16</sup> M.P. Schmidt\*,<sup>60</sup> M. Schmitt,<sup>37</sup> T. Schwarz,<sup>7</sup> L. Scodellaro,<sup>10</sup> A. Scribano<sup>cc</sup>,<sup>45</sup> F. Scuri,<sup>45</sup> A. Sedov,<sup>47</sup> S. Seidel,<sup>36</sup> Y. Seiya,<sup>40</sup> A. Semenov,<sup>14</sup> F. Sforza<sup>bb</sup>,<sup>45</sup> A. Sfyrla,<sup>23</sup> S.Z. Shalhout,<sup>7</sup> T. Shears,<sup>28</sup> P.F. Shepard,<sup>46</sup> M. Shimojima<sup>s</sup>,<sup>54</sup> S. Shiraishi,<sup>12</sup> M. Shochet,<sup>12</sup> I. Shreyber,<sup>35</sup> A. Simonenko,<sup>14</sup> P. Sinervo,<sup>32</sup> A. Sissakian\*,<sup>14</sup> K. Sliwa,<sup>55</sup> J.R. Smith,<sup>7</sup> F.D. Snider,<sup>16</sup> A. Soha,<sup>16</sup> S. Somalwar,<sup>51</sup> V. Sorin,<sup>4</sup> P. Squillacioti,<sup>16</sup> M. Stancari,<sup>16</sup> M. Stanitzki,<sup>60</sup> R. St. Denis,<sup>20</sup> B. Stelzer,<sup>32</sup> O. Stelzer-Chilton,<sup>32</sup> D. Stentz,<sup>37</sup> J. Strologas,<sup>36</sup> G.L. Strycker,<sup>33</sup> Y. Sudo,<sup>54</sup> A. Sukhanov,<sup>17</sup> I. Suslov,<sup>14</sup> K. Takemasa,<sup>54</sup> Y. Takeuchi,<sup>54</sup> J. Tang,<sup>12</sup> M. Tecchio,<sup>33</sup> P.K. Teng,<sup>1</sup> J. Thom<sup>g</sup>,<sup>16</sup> J. Thome,<sup>11</sup> G.A. Thompson,<sup>23</sup> E. Thomson,<sup>44</sup> P. Ttito-Guzmán,<sup>30</sup> S. Tkaczyk,<sup>16</sup> D. Toback,<sup>52</sup> S. Tokar,<sup>13</sup> K. Tollefson,<sup>34</sup> T. Tomura,<sup>54</sup> D. Tonelli,<sup>16</sup> S. Torre,<sup>18</sup> D. Torretta,<sup>16</sup> P. Totaro<sup>ff</sup>,<sup>53</sup> M. Trovato<sup>dd</sup>,<sup>45</sup> Y. Tu,<sup>44</sup> F. Ukegawa,<sup>54</sup> S. Uozumi,<sup>26</sup> A. Varganov,<sup>33</sup> F. Vázquez<sup>k</sup>,<sup>17</sup> G. Velev,<sup>16</sup> C. Vellidis,<sup>3</sup> M. Vidal,<sup>30</sup> I. Vila,<sup>10</sup> R. Vilar,<sup>10</sup> J. Vizán,<sup>10</sup> M. Vogel,<sup>36</sup> G. Volpi<sup>bb</sup>,<sup>45</sup> P. Wagner,<sup>44</sup> R.L. Wagner,<sup>16</sup> T. Wakisaka,<sup>40</sup> R. Wallny,<sup>9</sup> S.M. Wang,<sup>1</sup> A. Warburton,<sup>32</sup> D. Waters,<sup>29</sup> M. Weinberger,<sup>52</sup> W.C. Wester III,<sup>16</sup> B. Whitehouse,<sup>55</sup> D. Whiteson,<sup>8</sup> A.B. Wicklund,<sup>2</sup> E. Wicklund,<sup>16</sup> S. Wilbur,<sup>12</sup> F. Wick,<sup>25</sup> H.H. Williams,<sup>44</sup> J.S. Wilson,<sup>38</sup> P. Wilson,<sup>16</sup> B.L. Winer,<sup>38</sup> P. Wittich<sup>g</sup>,<sup>16</sup> S. Wolbers,<sup>16</sup> H. Wolfe,<sup>38</sup> T. Wright,<sup>33</sup> X. Wu,<sup>19</sup> Z. Wu,<sup>5</sup> K. Yamamoto,<sup>40</sup> J. Yamaoka,<sup>15</sup> T. Yang,<sup>16</sup> U.K. Yang<sup>p</sup>,<sup>12</sup> Y.C. Yang,<sup>26</sup> W.-M. Yao,<sup>27</sup> G.P. Yeh,<sup>16</sup> K. Yi<sup>m</sup>,<sup>16</sup> J. Yoh,<sup>16</sup> K. Yorita,<sup>57</sup> T. Yoshida<sup>j</sup>,<sup>40</sup> G.B. Yu,<sup>15</sup> I. Yu,<sup>26</sup> S.S. Yu,<sup>16</sup> J.C. Yun,<sup>16</sup> A. Zanetti,<sup>53</sup> Y. Zeng,<sup>15</sup> and S. Zucchelli<sup>z6</sup>

(CDF Collaboration<sup>†</sup>)

<sup>1</sup>*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*

<sup>2</sup>*Argonne National Laboratory, Argonne, Illinois 60439, USA*

<sup>3</sup>*University of Athens, 157 71 Athens, Greece*

<sup>4</sup>*Institut de Física d'Altes Energies, ICREA, Universitat Autònoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*

<sup>5</sup>*Baylor University, Waco, Texas 76798, USA*

<sup>6</sup>*Istituto Nazionale di Fisica Nucleare Bologna, <sup>z</sup>University of Bologna, I-40127 Bologna, Italy*

<sup>7</sup>*University of California, Davis, Davis, California 95616, USA*

<sup>8</sup>*University of California, Irvine, Irvine, California 92697, USA*

<sup>9</sup>*University of California, Los Angeles, Los Angeles, California 90024, USA*

<sup>10</sup>*Instituto de Física de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*

<sup>11</sup>*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*

<sup>12</sup>*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*

<sup>13</sup>*Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*

<sup>14</sup>*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*

<sup>15</sup>*Duke University, Durham, North Carolina 27708, USA*

<sup>16</sup>*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*

<sup>17</sup>*University of Florida, Gainesville, Florida 32611, USA*

<sup>18</sup>*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*

<sup>19</sup>*University of Geneva, CH-1211 Geneva 4, Switzerland*

<sup>20</sup>*Glasgow University, Glasgow G12 8QQ, United Kingdom*

<sup>21</sup>*Harvard University, Cambridge, Massachusetts 02138, USA*

<sup>22</sup>*Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland*

<sup>23</sup>*University of Illinois, Urbana, Illinois 61801, USA*

<sup>24</sup>*The Johns Hopkins University, Baltimore, Maryland 21218, USA*

<sup>25</sup>*Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany*

<sup>26</sup>*Center for High Energy Physics: Kyungpook National University,*

*Daegu 702-701, Korea; Seoul National University, Seoul 151-742,*

*Korea; Sungkyunkwan University, Suwon 440-746,*

*Korea; Korea Institute of Science and Technology Information,*

*Daejeon 305-806, Korea; Chonnam National University, Gwangju 500-757,*

*Korea; Chonbuk National University, Jeonju 561-756, Korea*

<sup>27</sup>*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

<sup>28</sup>*University of Liverpool, Liverpool L69 7ZE, United Kingdom*

<sup>29</sup>*University College London, London WC1E 6BT, United Kingdom*

<sup>30</sup>*Centro de Investigaciones Energeticas Medioambientales y Tecnológicas, E-28040 Madrid, Spain*

<sup>31</sup>*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

- <sup>32</sup>*Institute of Particle Physics: McGill University, Montréal, Québec, Canada H3A 2T8; Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6; University of Toronto, Toronto, Ontario, Canada M5S 1A7; and TRIUMF, Vancouver, British Columbia, Canada V6T 2A3*
- <sup>33</sup>*University of Michigan, Ann Arbor, Michigan 48109, USA*
- <sup>34</sup>*Michigan State University, East Lansing, Michigan 48824, USA*
- <sup>35</sup>*Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia*
- <sup>36</sup>*University of New Mexico, Albuquerque, New Mexico 87131, USA*
- <sup>37</sup>*Northwestern University, Evanston, Illinois 60208, USA*
- <sup>38</sup>*The Ohio State University, Columbus, Ohio 43210, USA*
- <sup>39</sup>*Okayama University, Okayama 700-8530, Japan*
- <sup>40</sup>*Osaka City University, Osaka 588, Japan*
- <sup>41</sup>*University of Oxford, Oxford OX1 3RH, United Kingdom*
- <sup>42</sup>*Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, <sup>aa</sup>University of Padova, I-35131 Padova, Italy*
- <sup>43</sup>*LPNHE, Université Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France*
- <sup>44</sup>*University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
- <sup>45</sup>*Istituto Nazionale di Fisica Nucleare Pisa, <sup>bb</sup>University of Pisa, <sup>cc</sup>University of Siena and <sup>dd</sup>Scuola Normale Superiore, I-56127 Pisa, Italy*
- <sup>46</sup>*University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA*
- <sup>47</sup>*Purdue University, West Lafayette, Indiana 47907, USA*
- <sup>48</sup>*University of Rochester, Rochester, New York 14627, USA*
- <sup>49</sup>*The Rockefeller University, New York, New York 10065, USA*
- <sup>50</sup>*Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, <sup>ee</sup>Sapienza Università di Roma, I-00185 Roma, Italy*
- <sup>51</sup>*Rutgers University, Piscataway, New Jersey 08855, USA*
- <sup>52</sup>*Texas A&M University, College Station, Texas 77843, USA*
- <sup>53</sup>*Istituto Nazionale di Fisica Nucleare Trieste/Udine, I-34100 Trieste, <sup>ff</sup>University of Trieste/Udine, I-33100 Udine, Italy*
- <sup>54</sup>*University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
- <sup>55</sup>*Tufts University, Medford, Massachusetts 02155, USA*
- <sup>56</sup>*University of Virginia, Charlottesville, VA 22906, USA*
- <sup>57</sup>*Waseda University, Tokyo 169, Japan*
- <sup>58</sup>*Wayne State University, Detroit, Michigan 48201, USA*
- <sup>59</sup>*University of Wisconsin, Madison, Wisconsin 53706, USA*
- <sup>60</sup>*Yale University, New Haven, Connecticut 06520, USA*

We report the most sensitive direct search for pair production of fourth-generation bottom-like chiral quarks ( $b'$ ) each decaying promptly to  $tW$ . We search for an excess of events with an electron or muon, at least five jets (one identified as due to a  $b$  or  $c$  quark) and an imbalance of transverse momentum using data from  $p\bar{p}$  collisions collected by the CDF II detector at Fermilab with an integrated luminosity of  $4.8 \text{ fb}^{-1}$ . We observe events consistent with background expectation and calculate upper limits on the  $b'$  pair production cross section ( $\sigma_{b\bar{b}'} \lesssim 30 \text{ fb}$  for  $m_{b'} > 375 \text{ GeV}/c^2$ ) and exclude  $m_{b'} < 372 \text{ GeV}/c^2$  at 95% confidence level.

PACS numbers: 12.60.-i, 13.85.Rm, 14.65.-q, 14.80.-j

---

\*Deceased

<sup>†</sup>With visitors from <sup>a</sup>University of Massachusetts Amherst, Amherst, Massachusetts 01003, <sup>b</sup>Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy, <sup>c</sup>University of California Irvine, Irvine, CA 92697, <sup>d</sup>University of California Santa Barbara, Santa Barbara, CA 93106 <sup>e</sup>University of California Santa Cruz, Santa Cruz, CA 95064, <sup>f</sup>CERN, CH-1211 Geneva, Switzerland, <sup>g</sup>Cornell University, Ithaca, NY 14853, <sup>h</sup>University of Cyprus, Nicosia CY-1678, Cyprus, <sup>i</sup>University College Dublin, Dublin 4, Ireland, <sup>j</sup>University of Fukui, Fukui City, Fukui Prefecture, Japan 910-0017, <sup>k</sup>Universidad Iberoamericana, Mexico D.F., Mexico, <sup>l</sup>Iowa State University, Ames, IA 50011, <sup>m</sup>University of Iowa, Iowa City, IA 52242, <sup>n</sup>Kinki University, Higashi-Osaka City, Japan 577-8502, <sup>o</sup>Kansas State University, Manhattan, KS 66506, <sup>p</sup>University of Manchester, Manchester M13

The standard model (SM) of particle physics accommodates three generations of fundamental fermions, but is agnostic on the issue of a fourth generation. Precision measurements in the electroweak sector are not inconsistent with a fourth-generation of fermions if there is a 50-

---

9PL, England, <sup>q</sup>Queen Mary, University of London, London, E1 4NS, England, <sup>r</sup>Muons, Inc., Batavia, IL 60510, <sup>s</sup>Nagasaki Institute of Applied Science, Nagasaki, Japan, <sup>t</sup>National Research Nuclear University, Moscow, Russia, <sup>u</sup>University of Notre Dame, Notre Dame, IN 46556, <sup>v</sup>Universidad de Oviedo, E-33007 Oviedo, Spain, <sup>w</sup>Texas Tech University, Lubbock, TX 79609, <sup>x</sup>Universidad Tecnica Federico Santa Maria, 110v Valparaiso, Chile, <sup>y</sup>Yarmouk University, Irbid 211-63, Jordan, <sup>gg</sup>On leave from J. Stefan Institute, Ljubljana, Slovenia,

100 GeV/ $c^2$  splitting in the quark and lepton masses [1]. A four-generation model [2] could provide a source of particle-antiparticle asymmetry large enough to account for the baryon asymmetry of the universe [3], and accommodate a heavier Higgs boson (the source of mass generation) than a three-generation model [4]. Direct searches for production of chiral fourth generation quarks restrict their masses to be greater than 335 GeV/ $c^2$  [5] for an up-type quark  $t'$  decaying via  $t' \rightarrow Wq$  and 338 GeV/ $c^2$  [6] for a down-type quark  $b'$  decaying via  $b' \rightarrow tW$ .

This Letter reports a search for pair-production via strong interactions of a heavy chiral [7] bottom-like quark,  $b'$ , followed by prompt decay to a  $t$  quark and a  $W$  boson with  $\mathcal{B}(b' \rightarrow tW) = 100\%$ . The assumption that  $b'$  decays exclusively to  $tW$  is reasonable if the coupling to light quarks is small, as expected from precision meson-mixing measurements [8], and in the hypothesis that  $m_{b'} > m_t + m_W$ . In the case that the branching fraction deviates from 100%, the limits can be interpreted under different assumptions [9]. Previous searches considered the mode in which two same-charge  $W$  bosons decayed leptonically [6], which gives a low-background signature but a low selection efficiency due to the small  $W \rightarrow \ell\nu$  branching ratio. We consider the mode  $b'\bar{b}' \rightarrow WtW\bar{t} \rightarrow WWbWW\bar{b} \rightarrow \ell\nu qq' b\bar{q}' q\bar{q}' b$  in which one  $W$  boson decays leptonically (including  $\tau$  decays to  $e$  or  $\mu$ ) and the remaining three  $W$  bosons decay hadronically, giving a selection efficiency nearly four times the previous search. The larger SM backgrounds can be separated from a potential signal by comparing the total reconstructed transverse momentum in the event.

Events were recorded by CDF II [10, 11], a general purpose detector designed to study collisions at the Fermilab Tevatron  $p\bar{p}$  collider at  $\sqrt{s} = 1.96$  TeV. A charged-particle tracking system immersed in a 1.4 T magnetic field consists of a silicon microstrip tracker and a drift chamber. Electromagnetic and hadronic calorimeters surround the tracking system and measure particle energies. Drift chambers located outside the calorimeters detect muons. We use a data sample corresponding to an integrated luminosity of  $4.8 \pm 0.3 \text{ fb}^{-1}$ .

The data acquisition system is triggered by  $e$  or  $\mu$  candidates [12] with transverse momentum ( $p_T$ [11]) greater than 18 GeV/ $c$ . Electrons and muons are reconstructed offline and selected if they have a pseudorapidity ( $\eta$ [11]) magnitude less than 1.1,  $p_T \geq 20$  GeV/ $c$  and satisfy the standard CDF identification and isolation requirements [12]. Jets are reconstructed in the calorimeter using the JETCLU [13] algorithm with a clustering radius of 0.4 in azimuth-pseudorapidity space and corrected using the standard techniques [14]. Jets are selected if they have  $p_T \geq 15$  GeV/ $c$  and  $|\eta| < 2.4$ . Each jet is considered for heavy-flavor tagging using the default CDF  $b$ -jet identification algorithm (SECVTX[15]) that searches in the jet for a secondary vertex which results from the displaced decay of a  $B$ -hadron inside the jet. Missing

transverse momentum [16] is reconstructed using fully corrected calorimeter and muon information [12].

Production and decay of  $b'$  pairs would appear as events with a charged lepton and missing transverse momentum from one leptonically decaying  $W$ , and a large number of jets from the two  $b$  quarks and the hadronic decays of the other three  $W$  bosons. We select events with exactly one electron or muon, at least five jets, and at least 20 GeV/ $c$  of missing transverse momentum. At least one of the jets must be identified as due to  $b$  quark decay. We find 357 events satisfying these requirements.

We model the production and decay of  $b'$  pairs with MADGRAPH [17]. Additional radiation, hadronization and showering are described by PYTHIA [18]. The detector response for all simulated samples is modeled by CDFSIM [19]. The signal efficiency for the above requirements is approximately 10%, rising with  $b'$  mass. There are eight quarks produced in the decay, but the most likely number of reconstructed jets is six, as quarks that are close together are likely to be merged into a single jet, and some of the quarks produce jets which fall below the transverse momentum threshold. Complete mass reconstruction is therefore not possible in the majority of the events; instead, we examine the event  $H_T$ , the scalar sum of the transverse momentum of the lepton, jets and missing transverse momentum. This is well correlated with the mass of the heavy quark and serves as an approximate mass reconstruction.

The dominant background (80%) is top-quark pair production with additional jets from initial or final state radiation. This background can be distinguished from the signal as it has smaller  $H_T$ . We model this background using MADGRAPH  $t\bar{t}$  production with  $m_t = 172.5$  GeV/ $c^2$  in which radiation of up to three additional hard partons (including heavy flavor) are described explicitly using matrix-elements, and additional radiation is described by the parton-shower; the MLM [20] scheme is used to match the matrix-element and parton-shower contributions. This gives a precise description of events with  $\leq 7$  jets, where a  $b'$  signal would be expected. Events with eight jets and above are described by the parton shower, which has significantly larger systematic uncertainties. We normalize the  $t\bar{t}$  background to the NLO cross section [28], and confirm that it is well modeled by examining  $t\bar{t}$ -dominated regions in the data.

The second dominant background process ( $\approx 10\%$ ) is the associated production of  $W$  boson and jets. Samples of simulated  $W$ +jets events with light- and heavy-flavor jets are generated using the ALPGEN [21] program, interfaced with parton-shower model from PYTHIA. The  $W$ +jets samples are normalized to the measured  $W$  cross section, with an additional multiplicative factor for the relative contribution of heavy- and light-flavor jets, the standard technique in measuring the top-quark pair production cross section [15]. Multi-jet background ( $\approx 5\%$ ), in which a jet is misreconstructed as a lepton, is modeled

using a jet-triggered sample normalized in a background-dominated region at low missing transverse momentum. The remaining backgrounds, single top and diboson production, are modeled using PYTHIA and normalized to next-to-leading order cross sections [22]. The combined background expectation is  $365 \pm 194$  events, including systematic and statistical uncertainties.

A  $b'$  signal would be readily separated from the background both in the number of jets and the  $H_T$ . To take advantage of both of these characteristics, we introduce a variable “Jet- $H_T$ ”, which equals  $H_T$  for events with exactly 5 jets,  $\text{Jet-}H_T = H_T + 1000$  GeV for events with exactly 6 jets, and  $\text{Jet-}H_T = H_T + 2000$  GeV for events with at least 7 jets. This is equivalent to a two-dimensional analysis in  $N_{jets}$  and  $H_T$ . Figure 1 shows the distributions of an example  $b'$  signal with  $m_{b'} = 350$  GeV/ $c^2$  and the backgrounds in Jet- $H_T$ .

We consider several sources of systematic uncertainty on both the background rates and distributions, as well as on the expectations for the signal. Each affects the expected sensitivity to new physics expressed as an expected cross section upper limit in the no-signal assumption. The dominant systematic uncertainties are the jet energy scale [14], contributions from additional interactions, and descriptions of initial and final state radiation [23]. In each case, we treat the unknown underlying quantity as a nuisance parameter and measure the distortion of the Jet- $H_T$  spectrum for positive and negative fluctuations. Each uncertainty weakens the expected 95% confidence level (C.L.) cross section upper limit by  $\approx 60\%$  individually. Additional uncertainty comes from parton distribution functions (PDF) [24, 25], the matching scale used between the matrix-element and the parton shower, overall background normalization, and uncertainties in performance of the  $b$ -quark identification algorithm. The overall impact on the expected sensitivity is  $\approx 100\%$  in the cross section and  $\approx 20$  GeV/ $c^2$  on the expected mass limit.

To validate the description of the backgrounds, we verify that the low  $H_T$  region is well-described where there is little signal expected. See Table I. In events with  $\geq 7$  jets, the observed  $H_T$  is larger than predicted by our background model. The number of observed events with  $\geq 7$  jets and  $H_T > 500$  GeV is 12 where we expect  $3.4 \pm 3.4$ . However, the total number of events observed in the low  $H_T$  and high  $H_T$  regions combined is consistent with expectation. Considering only the number of events in the high  $H_T$  regions and taking into account the systematic uncertainties in the background prediction, we see a more significant excess than that observed in the data in 12% of simulated experiments.

The full Jet- $H_T$  spectrum is used in the analysis. Since there is no evidence for the presence of  $b'$  events in the data, we calculate 95% C.L. upper limits on the  $b'$  production cross section, by performing a binned maximum-likelihood fit in the Jet- $H_T$  variable, allowing for sys-

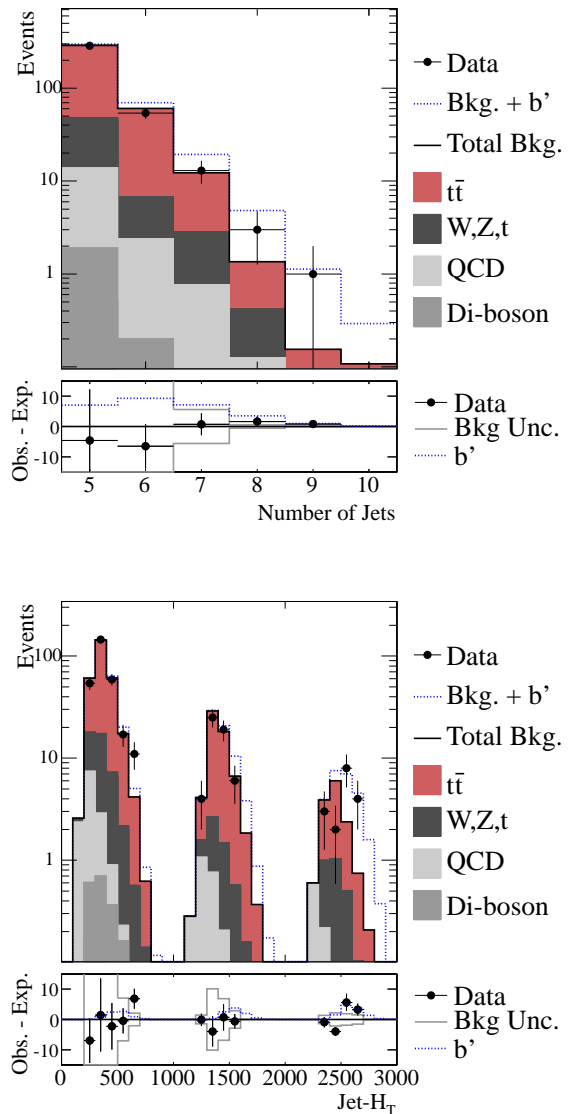


FIG. 1: Distributions in jet multiplicity and Jet- $H_T$  (defined in the text). The example  $b'$  signal has  $m_{b'} = 350$  GeV/ $c^2$  and would have  $29 \pm 4.5$  events expected in this sample. Top pane is log scale; bottom pane shows the difference between expected and observed events on a linear scale, as well as the total uncertainty on the expected events.

tematic and statistical fluctuations via template morphing [26]. We use the likelihood-ratio ordering prescription [27] to construct classical confidence intervals in the theoretical cross section by generating ensembles of simulated experiments that describe expected fluctuations of statistical and systematic uncertainties on both signal and backgrounds. The observed limits are consistent with expectation in the background-only hypothesis and are given together with theoretical next-to-leading-order (NLO) cross sections [28, 29] in Table II and shown in

TABLE I: Expected and observed events in a background-dominated control region ( $H_T < 400, 450, 500$  for  $N_{jet} = 5, 6, \geq 7$ , respectively) and in a signal-dominated region ( $H_T > 400, 450, 500$  for  $N_{jet} = 5, 6, \geq 7$ ) for our selection (see text). Uncertainties are statistical and systematic, combined in quadrature.

Jets	Control Region		Signal Region		Sum	
	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
5	207 $\pm$ 125	199	84 $\pm$ 65	87	291 $\pm$ 190	286
6	43 $\pm$ 31	40	18 $\pm$ 12	14	61 $\pm$ 43	54
$\geq 7$	11 $\pm$ 3.9	5	3.4 $\pm$ 3.4	12	14 $\pm$ 7.1	17

Fig. 2.

We convert upper limits on the pair-production cross sections to lower limits on the fermion masses. The relative cross-section uncertainty of  $\approx 10\%$  due to scale and PDF uncertainties translates into  $\approx 3 \text{ GeV}/c^2$  for the mass lower limits.

In conclusion, we have searched for pair production of  $b'$  quarks with subsequent decay to  $tW$ . Though there are events with larger  $H_T$  than expected in the 7-jet event distribution in Fig 1, we do not see evidence of a signal. We calculate upper limits on the  $b'$  pair production cross section ( $\lesssim 30 \text{ fb}$  for  $m_{b'} > 375 \text{ GeV}/c^2$ ) and set the most restrictive direct lower limit on the mass of a down-type fourth-generation quark, increasing the limit by 34  $\text{GeV}/c^2$  to  $m_{b'} \geq 372 \text{ GeV}/c^2$  and significantly reducing the allowed mass range.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the World Class University Program, the National Research Foundation of Korea; the Science and Technology Facilities Coun-

TABLE II: Theoretical cross sections ( $\sigma_{\text{NLO}}$  in fb [28, 29]), expected  $b'$  yield ( $N_{\text{exp}}$ ) after selection, median expected 95% C.L. limit ( $\sigma_{\text{exp}}$  in fb), and observed 95% C.L. limit ( $\sigma_{\text{obs}}$  in fb) for  $b'$  at varying masses.  $\sigma_{\text{NLO}}$  and  $N_{\text{exp}}$  have 10% uncertainties.

Mass [ $\text{GeV}/c^2$ ]	260	300	325	350	375	400	425
$\sigma_{\text{NLO}}$	630	227	125	65	34	19	9.5
$N_{\text{exp}}$	203.2	91.5	53.0	28.1	14.9	7.6	4.0
$\sigma_{\text{exp}}$	72	49	40	34	34	34	34
$\sigma_{\text{obs}}$	72	72	66	53	36	33	34

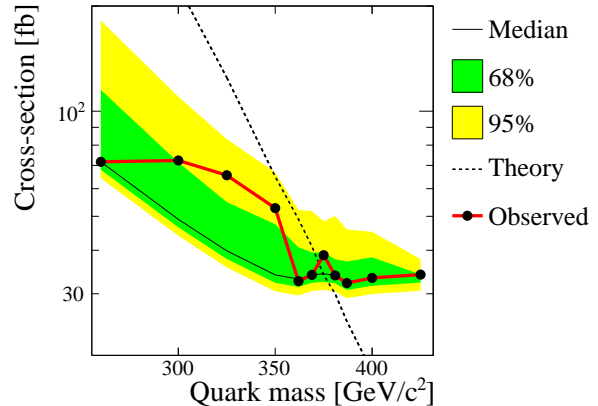


FIG. 2: Upper limits on  $b'$  production cross section at 95% C.L. assuming  $\mathcal{B}(b' \rightarrow tW)=100\%$ . Solid black line is the median expected upper limit in simulated experiments without  $b'$  signal; green and yellow bands represent 68% and 95% of simulated experiments, respectively; solid red line is the observed limit. Dashed black line is the NLO  $b'$  production cross section [28, 29].

cil and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

- [1] O. Cobanoglu, E. Ozcan, S. Sultansoy *et al.*, arXiv:1005.2784
- [2] P. Frampton, P. Hung, and M. Sher, Phys. Rept. **330**, 263 (2000).
- [3] W.-S. Hou, Chin. J. Phys. **47**, 134 (2009).
- [4] G. Kribs, T. Plehn, M. Spannowsky, and T. Tait, Phys. Rev. D **76**, 075016 (2007).
- [5] A. Lister, ICHEP2010, in preparation
- [6] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **104**, 091801 (2010).
- [7] We specify chiral quarks to distinguish from theories of a vector-like fourth generation.
- [8] O. Eberhardt, A. Lenz, and J. Rohrwild, arXiv:1005.3505
- [9] C. Flacco *et al.*, Phys. Rev. Lett. **105** (2010) 11801.
- [10] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 032001 (2005).
- [11] CDF uses a cylindrical coordinate system with the  $z$  axis along the proton beam axis. Pseudorapidity is  $\eta \equiv -\ln(\tan(\theta/2))$ , where  $\theta$  is the polar angle relative to the proton beam direction, and  $\phi$  is the azimuthal angle while  $p_T = |p| \sin \theta$ ,  $E_T = E \sin \theta$ .
- [12] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. Lett. **97**, 082004 (2006); D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **94**, 091803 (2005).
- [13] F. Abe *et al.* (CDF Collaboration), Phys. Rev. D **45**,

- 001448 (1992).
- [14] A. Bhatti *et al.*, Nucl. Instrum. Methods **566**, 375 (2006).
  - [15] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. D **74**, 072006 (2006).
  - [16] Missing transverse momentum,  $\cancel{E}_T$ , is defined as the magnitude of the vector  $-\sum_i E_T^i \vec{n}_i$  where  $E_T^i$  are the magnitudes of transverse energy contained in each calorimeter tower  $i$ , and  $\vec{n}_i$  is the unit vector from the interaction vertex to the tower in the transverse  $(x, y)$  plane.
  - [17] J. Alwall *et al.* J. High Energy Phys. 09 (2007) 028, version 4.4.24.
  - [18] T. Sjostrand *et al.*, Comput. Phys. Commun. **238** 135 (2001), version 6.422.
  - [19] E. Gerchtein *et al.*, arXiv:physics/0306031 (2003).
  - [20] M. Mangano, arXiv:hep-ph/0602031
  - [21] M. Mangano *et al.*, J. High Energy Phys. 07 (2003) 001.
  - [22] J. Campbell and R. Ellis, Phys. Rev. D **60** 113006 (1999).
  - [23] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. D. **73** 32003 (2006).
  - [24] J. Pumplin *et al.* (CTEQ Collaboration), J. High. Energy Phys. 07 (2002) 012.
  - [25] A. D. Martin *et al.* (MRST Collaboration), Phys. Lett. B **356** 89 (1995).
  - [26] A. Read, Nucl. Instrum. Methods A**425**:357-360 (1999).
  - [27] G. Feldman and R. Cousins, Phys. Rev. D **57**, 3873 (1998).
  - [28] R. Bonciani, S. Catani, M. L. Mangano, and P. Nason, Nucl. Phys. **B529**, 424 (1998).
  - [29] M. Cacciari, S. Frixione, M. L. Mangano, P. Nason, and G. Ridolfi, J. High Energy Phys. 04 (2004) 068.